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NANOTECHNOLOGY: MOLECULAR MOVERS AND SHAKERS

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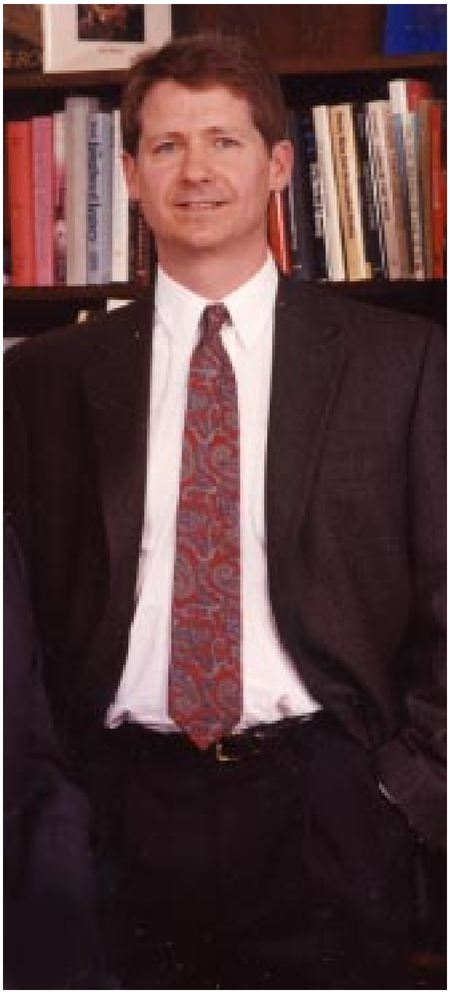

When nanotechnology became a buzzword about a decade ago, no one was quite sure what it was. Just how the field will develop is still unclear, but the past year has seen a transformation in its ability to attract public investment. The US federal government will almost double its spending on nanotech next year, to more than $400 million. Japan is planning a budget hike of more than 40 percent, and several European countries have made nanoscale research a priority. Nanotechnology looks poised to shed its science-fiction image and don the mantle of respectability.

But what opportunities should we expect to see the new funds create? The highlights of the past 12 months give some pointers. One of these is nanotechnology's potential to reinvent and revitalize chemistry. For example, chemists should have fun with nanotech's party piece, the manipulation of individual atoms using the scanning tunnelling microscope (STM).

In September, a team at the Free University of Berlin synthesized a biphenyl molecule from two benzene radicals using the STM[1]. Such piece-by-piece molecule-building, although impressive, is unlikely to replace standard chemical synthesis. But the combination of nanoscale manipulation and spontaneous chemical processes has huge potential.

This was shown in July by researchers at the Steacie Institute for Molecular Sciences in Ottawa, Canada[2]. Robert Wolkow and his colleagues used the STM to remove individual hydrogen atoms from a hydrogen-covered silicon surface. This allowed a styrene molecule to bind to the silicon, setting off a chain reaction in which a neighbouring hydrogen was displaced, another styrene bound to the silicon, and so on – resulting in rows of molecules up to 13 nanometres long.

In a similar vein, Stanley Williams and colleagues at the Hewlett-Packard Research Laboratories in Palo Alto, California, reported in June that they had made grid-like arrays of self-assembling erbium disilicide nanowires on a silicon substrate[3]. They anticipate using such grids in a memory-rich architecture for a nanoscale computer. And Williams's collaborator James Heath and his team at the University of California at Los Angeles have developed another of the building blocks for such a device: molecular switches that work at room temperature[4].

The connections in nanoscale circuits could well be made of conducting carbon nanotubes. And the discovery of a simple method for fashioning them into 'Y' shapes broadens their scope for use in electronic circuitry[5]. Conducting organic materials might open the way to a genuine molecular electronics – as was acknowledged by this year's chemistry Nobel.

The cell, meanwhile, is a ready-made toolbox of molecular machines, and biomolecular science is sure to be a big part of nanotechnology. By coupling the ability of specific biomolecules to recognize one another with manipulation using laser beams as optical tweezers, chemist George Whitesides and his colleagues at Harvard University this year explored the frontier with biology, making sculptures from red blood cells tagged with polymer microspheres[6].

In June, a paper from Angela Belcher and colleagues at the University of Texas at Austin united protein chemistry with semiconductor technology. They created peptides that can recognize and bind to the surfaces of different semiconductors[7]. This points to the possibility of devices based on biological molecules, such as the motor proteins that power cell movement, that can assemble electronic or other inorganic structures. The exciting beginnings of such a hybrid technology were heralded in November, with the report of a nanoscale metal rotor powered by the enzyme ATP synthase[8].

Practical applications remain years away. "Nanotechnology doesn't yet exist," says Don Eigler of IBM's Almaden Research Center in San Jose. But there is one concrete sign that nanoscale research will eventually deliver working technologies: the spin-off companies launched by some of the field's academic pioneers. In the past year, Richard Smalley of Rice University in Houston formed Carbon Nanotechnologies, which aims to commercialize the use of carbon nanotubes; and Chad Mirkin and co-workers at Northwestern University in Illinois have launched Nanosphere. This company seeks to use a system based on tiny gold particles to develop diagnostic tests that recognize particular sequences of DNA.

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DR ROBERT WOLKOW

NANOSCALE INFORMATION AND COMMUNICATIONS TECHNOLOGY

iCORE Chair
Physics
University of Alberta

Dr Robert Wolkow is leading a $10 million research program called Nanoscale Information and Communication Technologies, through his appointment as an iCORE Chair, affiliated with the Department of Physics at the University of Alberta and the National Research Council's National Institute for Nanotechnology. As the project is in a start-up phase, this brief report summarizes program goals and current research staff.

EXECUTIVE SUMMARY

The Nanoscale Information and Communications Technology group is in an initial start up phase at the University of Alberta, and will be associated with the new National Institute of Nanotechnology (NINT) in Edmonton. Initial projects will include investigations into nanoscale structure and manipulation, instrument development, connections to nanostructures, directed growth, and theory.

RESEARCH GOALS AND OBJECTIVES

The research team will continue to create and analyze complex hybrid silicon-organic structures in the near future in order to create a robust base on which to build hybrid silicon-organic devices. Some key projects:

Nanoscale structure

- *Determining Structure.* With spectroscopy, scanning tunneling microscopy and theory we will resolve the electronic structure of surface-molecule complexes. One goal is to control local band bending (in the substrate) via subtle but controlled adsorption processes. We see connections to switching, hybrid transistors, memory elements, and sensors.
- *Self-directed growth.* A substantial advance has been made in automatically growing well-defined molecular structures on a surface. We showed for the first time that arduous atom-by-atom crafting techniques are not the only way to build on the tiniest scale. Many extensions are soon to be published and underway including new mechanisms, new functionality and theory advances. Further elements of control are being sought. We aim for a parallel (simultaneous) molecular fabrication tool that provides atom-level control by merely turning valves. A patent is pending.
- *Understanding dynamics of adsorption.* This is as important as structural determinations in searching for phenomena inherent to the nanoscale that might underpin new technologies. Several years ago we capped 60 years of study, showing definitively

that molecules hover and search over a surface before settling in to form a chemical bond. That phenomenon is of general importance – it daily affects our thinking about building molecular structures.

Nanoscale manipulation

- *Spatially defined attachment points*. Further methods to alter substrate structure in order to create spatially defined attachment points for molecules will be pursued.
- *All in-vacuum nano-lithography*. This is being developed, at this point for one-off structures, to allow connection and testing of nanostructures.

Instrument development

- Technique development is always ongoing. We wish to be thought of as the premiere centre in the world for innovation in scanned probe and related nanoscience techniques. Today, scanned probe experiments are notoriously difficult. A machine will be built that is substantially more productive. Tips (the actual scanned probe) are intolerably unreliable. We are undertaking a program to create superior tips and instruments. We have credentials in this area, having created the world's first tunable temperature cryogenic STM, a machine that greatly expanded the scope of accessible nano-scale phenomena.

Connections to nanostructures
In order to use nanostructures we must find means to address them. The focus is on self-forming and well-defined connections. Connections must be defined in absolute position and in terms of internal structure. Most work to date has created structurally ill-defined connections. Our molecule-silicon studies have solved the most complex silicon interface problems approached to date and as a result we are ideally positioned to lead in this area.

"Connected STM"
At this stage, we need a machine that facilitates connection to single nanoscale entities – thereby avoiding the need for extensive (or, at this point, impossible) lithographic steps.

Growing contacts to silicon
We will extend our work on well-defined $TiSi_2$ contacts. These are attractive as they withstand harsh thermal and chemical conditions and present a very small Schottky barrier. Methods for defining very closely spaced contacts on silicon are being developed. These will allow ultra-small, functionalized silicon surface regions to be probed. Early applications will include measurements of chemi-electric-field control of near-surface conductive channel structures.

Local doping control
Local doped regions will provide another attractive method for creating silicon surface contacts. In addition to conventional dopants (defined lithographically and with focused ion beam) we aim to create a new class of surface bound (as opposed to substitutional/bulk) dopants which can act without high temperature annealing/ activation and which will be restricted to a plane. This technique could find near term application (to be patented if warranted).

Directed growth
A variety of schemes for efficient, controlled growth of nano-structures will be explored. This is a centrally important issue. Self-assembly will be key to nano/ molecular technologies.

- *Field directed growth*. Field controlled approaches may provide one way to efficiently control nano-structure growth. A patent application has been prepared.
- *Chemically directed growth*. We will attempt to have molecules find their intended docking points by employing chemical "lock and key" methods.
- *Assisting assembly*. Many of the components we wish to manipulate are too large to migrate freely, hampering assembly. We are devising novel methods for assisting motion.

Theory
Theory has and will continue to be an essential part of our work. Theory doesn't stand apart as perhaps suggested by this section; it is integrated with all of the above.

- Structure of molecular-substrate complexes
    1. as determined by strong chemical bonds
    2. and as determined by relatively weak physical interactions
- Dynamics of structures

1. barriers which control growth processes
2. fluctuations in existing structures that can embody the function of the nanostructure (for example a field-induced structural change that allows a charge (electron or hole) to be stored)

- Tunneling transmission through well-defined structures will likely prove useful in molecular devices.
- Electrostatic calculations like those used for present semiconductor devices, will be used to predict and understand the control of channel conduction as a function of the configuration of surface mounted nanostructures.

Exploratory Devices
These will be fabricated to test and develop ideas. These projects will be broadly collaborative and interdisciplinary.

- Molecular computation devices will be made as soon as possible. Knowing how to achieve connection/addressing will likely be best explored with sensing devices first.
- Molecular sensing
  1. Earliest designs will make a kind of pressure sensor-the adsorption of molecules will be detected. This will serve to test the viability of our scheme and then as a vehicle for assessing and extending sensitivity. Engineers must be engaged as partners.
  2. Biological molecules provide an endlessly varied and lucrative target for detection technology. The challenge is an order of magnitude greater than the pressure sensor above. Tight collaboration with (bio)chemical/medical experts will be engaged.

RESEARCH PROJECTS

The team for Nanoscale Information and Communications Technology is still in transition, as the project has just recently started. Arrangements are underway for moving staff and equipment to the University of Alberta and NINT.

RESEARCH TEAM

TEAM LEADER	TITLE
Bob Wolkow	iCORE Chair in Nanoscale Information and Communications Technology
OTHER TEAM MEMBERS	**TITLE/TOPIC**
Jason Pitters	Staff Scientist/Ultra High Vacuum Scanned Probe Microscopes
Gino DiLabio	Staff Scientist/Quantum Chemistry Theorist
Doug Moffatt	Technician
Carmen Remenda	Administrative Assistant

POSTDOCTORAL RESEARCHERS	TOPIC
Mohamed Rezeq	Field Ion Microscopy
Paul Piva	Hybrid Molecular-silicon Structures
Adam Dickie	Silicon Nanostructures
Lin Wu	Engineering Nanoscale Machinery

COLLABORATIONS

Dr Werner Hofer, who collaborates with Paul Piva, is a new lecturer at Liverpool and an expert in solid-state density functional calculations. Professor Alain Rochefort, Département de génie physique, École Polytechnique de Montréal and Centre de Recherche en Calcul Appliqué (CERCA), is a theorist with expertise molecular interactions related to electrical transport, also working on the Piva project.

THE NANOSCALE INFORMATION AND COMMUNICATION TECHNOLOGIES RESEARCH PROGRAM AIMS TO BE THOUGHT OF AS THE PREMIERE CENTRE IN THE WORLD FOR INNOVATION IN SCANNED PROBE AND RELATED NANOSCIENCE TECHNIQUES.

Dr Yuh-Lin Wang of Academia Sinica in Taiwan (Chemical Physics) is an expert in focused ion beam instruments, nanostructures and scanned probe microscopy. He has worked with Dr Wolkow for two years on a project that aims to connect small numbers of molecules to macroscopic electrodes, allowing direct electrical characterization of hybrid silicon-molecular structures. In conjunction with Dr Wang, the team is fabricating (in Taiwan) and making ultra high vacuum measurements (in Canada) of the small structures described above.

Dr ChiiDong Chen of Academia Sinica in Taiwan (Physics) is an expert in low temperature characterization of solid-state semiconductor structures and in lithography, including ebeam. In conjunction with Dr Wang, the team fabricating (in Taiwan) and studying (in Canada) the small structures described above.

Professor Andrew Fisher of University College London has worked with Dr Wolkow for several years on joint experimental-theoretical studies of molecules on silicon. The team plans a unique, exciting joint effort that will address ways to gain a new level of control over semiconductor electronic properties via surface chemical control.